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PRIMARY HETEROGENEITIES OF THE EARTH'S MANTLE

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A study of the accumulation process of the earth from solid bodies and particles by the methods embraced by the theory of coagulation prompts us to conclude that a considerable portion of the mass of accumulated matter had been concentrated in large bodies. The dropping of large bodies to the earth at random directed velocities resulted in deflecting the direction of its rotation from that of "direct rotation". From the angle of inclination of the earth's equator to the ecliptic it was found that the masses of the greatest bodies falling to earth were about a thousandth part of the earth's mass, i.e., with cross sections of about 1,000 km. The slight differences in density and composition of large bodies could have resulted in noticeable heterogeneities in the earth's mantle. The falling of bodies with diameters in the hundreds of kilometers was accompanied by the heating of a vast region in the zone of contact creating marked thermic heterogeneities of the earth's mantle which could have been preserved over a period of a billion years or more, and then be sustained in the upper mantle through the dissipation of energy of lunar tides. The possibility of the prolonged existence of excessively regions in the upper mantle with dimensions of several thousand kilometers opens the door for explaining the reasons for this difference between continents and oceans.

Recently, a number of independent data have been produced which point to the fact that within the earth's mantle there are found marked horizontal

heterogeneities of various orders of magnitude extending through various depths of the mantle. Clearly standing out on a gravimetric chart are the positive and negative gravitational anomalies which embrace a region with a diameter of several thousand kilometers [1]. An analysis of the zonal harmonics of the earth's gravitational potential obtained from observations of artificial earth satellites [2, 3] demonstrated [4, 5] that the anomalies observed are considerably greater and more opposite in sign than the anomalies computed for continents assuming a hydrostatic equilibrium (isostasy). They cannot be produced by the various densities in the core and are undoubtedly associated with horizontal heterogeneities of a large scale in the earth's mantle. From studies of tidal deformations of the earths core [6] it follows that the resilient properties of the earth's mantle in the European portion of the USSR and in Central Asia differ considerably. Seismic and electromagnetic observations also point to the existence of regional horizontal heterogeneities in the earth's mantle [7, 8].

Also pointing to large horizontal heterogeneities is the existence of oceans and continents. It is very unlikely that such large scale formations could appear in the original, quasihomogeneous earth. Hence, the presence of oceans and continents could more likely be regarded as an indication of the existence in the earth's mantle of original heterogeneities of a large scale.

Information essential to geophysics regarding the initial state of the earth can be obtained on the basis of cosmogonic considerations. According to the present theory of the origin of planets, the earth was formed through the accumulation of solid substances -- particles and bodies of various sizes. The falling upon the earth of large bodies could have produced the original heterogeneities of the earth's mantle.

The maximum dimensions of bodies falling to the earth. A study of the process of unifications of matter into planets by the methods suggested in the theory of coagulation permits us in principle to determine the function of distribution of bodies during the course of the entire process. If we assume that the colliding bodies merely unite and do not subdivide we then get the usual equation for coagulation

$$\frac{\partial n(m,t)}{\partial t} = \frac{m}{2}\int_0^m A(m', m-m')\,n(m',t)\,n(m-m',t)\,dm' - \\ - n(m,t)\int_0^\infty A(m,m')\,n(m',t)\,dm', \tag{1}$$

in which n(m,t) is the number of particles of mass m in a unit volume; A(m,m') is the effectivenss of coagulation of masses m and m'; t is the time. If we account for the subdivision of colliding particles we get a generalized equation of coagulation with additional members on the right side of the equation (1). But even for a simple equation (1) a precise solution can be obtained only in a few more simple cases. The well known classic solution by M. Smolukhovskiy [9] with A(m,m') = const is not adequate because in the process of accumulation of protoplanetary bodies A(m,m') changes within broad limits.

In study [10] we found a precise solution to equation (1) with the coefficient of coagulation $A(m,m') = A_1(m + m')$, which is selected as a certain "reasonable mean" section of collision between sections for small particles and bodies ($\sim m^{2/3}$ with $m > m'$) and the section for large gravitating bodies ($\sim m^{4/3}$). The distribution function in this case appears as follows:

$$n(m,\tau) = \frac{N_0(1-\tau)}{m\sqrt{\tau}}e^{-bm(1+\tau)}I_1(2bm\sqrt{\tau}), \tag{2}$$

in which

$$\tau = 1 - e^{-A_1Mt};\; b = N_0/M;\; n(m,\,0) = N_0be^{-bm};$$

M and N_0 are the mass and original number of particles in a unit of volume; A_1 = const, I_1 (x) is a modified Bessel function. Practically throughout the

entire interval of change m (excluding the largest and smallest m) the distribution function (2) can be approximated by exponential function $m^{-3/2}$. It is important to note that in this distribution a large portion of the mass in the system consists of large bodies. The fragmentations of bodies alter their distribution, decreasing the relative mass of larger bodies. However, the importance of the large bodies in the formation of the earth is considerable. It is interesting to note that the distributions by masses of asteroids and meteorites dropping to the earth, as found through observations which satisfactorily approximate the exponential law with the indexes, are also close to 3/2.

The masses of the largest bodies which dropped on planets during the process of their formation can be evaluated from the observed inclinations of axes of rotation of planets [11]. The latter consists of two components different in nature: the regular or "direct rotation" associated with the rotation of the entire system, and the irregular rotation, which is associated with velocities of bodies falling upon it that are random with respect to planet. The random component is determined, mainly, by the fall of large bodies and causes the inclination of the planet's axis of rotation. For the exponential law of distribution of masses of bodies $n(m,t) = f(t)m^{-q}$ we get the following correlation between the relationship of the mass m_1 of the greatest body to the mass of the planet m and the planet's axis of rotation ε:

$$\frac{m_1}{m_2} = \frac{3-q}{2-q}\,\frac{10}{3(1-1/2\theta)}\left(\frac{4C\sin\varepsilon}{\pi}\,\frac{v_r}{v_c}\right)^2 \qquad (3)$$

in which v_r is the speed of rotation at the planet's equator; $v_c = \sqrt{Gm/r}$, r is the radius of the planet; C is the factor in the expression for the moment of inertia of the Planet $I = Cmr^2$; θ is the factor of the order of unity in the expression for the relative velocity of bodies to an approach

with the planet $v = \sqrt{GM/\theta r}$. Taking for the earth $\mathcal{E} = 23.5$, $C = 0.33$, and having accepted $q = 3/2$, $\theta = 3$ we find $m_1/m \sim 10^{-3}$. Hence the masses of the largest bodies falling upon the earth during its formation were of the order of a thousandth portion of the earth's mass. Their diameters were of the order of a thousand kilometers. In keeping with the theory of tides the value of $v_r \sin \mathcal{E}$ in the past for the earth was greater than it is now [12]. This results in a greater value of m_1/m than is given by (3) from the present rotation of the earth.

This result is in agreement with an independent evaluation of the effective dimensions of bodies which were captured by the earth as a result of non-resilient collisions near it, and they formed a satellite swarm around the earth. According to [13,14] the total mass of the lunar cluster [dolunnyy roy] is equal to the mass of the moon with the effective radius of colliding bodies being between 10 and 10^2 km.

A visual illustration of the considerable importance of the large bodies in the process of forming planets and their satellites are the lunar craters and seas. Lunar seas were formed as a result of the falling of planetesimals with diameters of several tens of kilometers.

<u>Difference in chemical composition of bodies</u>. The chemical composition of planets changes regularly with the distance from the sun. The interior planets are considerably denser than the exterior ones. Urey detected the difference in the density of rocky meteorites up to 0.2 g/cm^3; this, apparently is associated with the formation of parental families of meteorites in the different regions of the asteroid belt. Also found was the difference in the composition of iron meteorites. At standard pressure the substance of the planet Mercury is the densest in the solar system. Not excluded is the possibility that the substance of Venus is a few percentile points denser than

the substance of the earth [16]. The feeding zone for the earth as it was being formed extended practically from the orbit of Venus to that of Mars. It can be expected that bodies formed in different parts of this broad zone had differences in composition and density varying by several percent.

If the bodies went into the makeup of the earth in their approximately original form as local inclusions they should have introduced marked heterogeneities in the earth's mantle and caused a movement in it. With a density threshold of the mantle substance ranging from 10 to 10^2 bar, inclusions with diameters of several tens of kilometers and a density greater or less than the density of the surrounding substance by 0.1 g/cm^3 should have risen or sunk under the effect of gravitational forces. The movement of larger inclusions may have begun with smaller differences in density. When the inclusions were of sufficiently large dimensions the differentiation might have commenced immediately after the formation of the earth. Displacements of smaller inclusions began only after a certain amount of heating and decrease in viscosity of the surrounding substance of the mantle.

Difference in composition of bodies may have been manifested not only as differences of their density but also in the differences of radioactive elements contained (also of the order of a few percent). Both may have existed simultaneously, but in contrast with the first, the latter were not immediately manifested. Inclusions with an excess of radioactive elements in the process of disintegration were heated somewhat more rapidly, and then gradually became less dense than the surrounding substance. In these regions the partial fusion of silicates, the upheaval of these fusions, and the formation of the earth's core occurred earlier.

<u>Aftereffects of large bodies falling to the earth and the evolution of heat in the area of strike</u>. It was previously demonstrated that bodies that

fell to the earth were sufficiently large and may have differed in chemical composition. If they had entered the composition of the earth as individual inclusions they might have created marked heterogeneities in its mantle. However, bodies dropping to the earth at velocities of 10 - 12 km/sec would have disintegrated and their substances scattered over a large area. Hence, the heterogeneities associated with the difference in composition of falling bodies were smoothed out very markedly. Data on the distribution of substances of a fallen body over a surface are extremely meager. There is some experimental evidence [17] pointing to the existence in certain cases of cumulative effects resulting in the assembly of a considerable portion of the fallen substance in the central portion of the crater. Attempts are being made to explain the presence of the centrally located small hills in many of the lunar craters [18]. If the central hillocks actually consist of fragments of the fallen body to a large extent, the heterogeneities introduced by the bodies may be more markedly expressed. However, extrapolating experimental data (a study was made of the fall of a colored droplet into a vessel containing water) to phenomena on a cosmic scale (collisions between bodies a hundred km in diameter) is still too unreliable to permit drawing conclusions of any reliability on such extrapolations. When very large bodies fall the essential role should be played by the force of gravitation, which limited the possibility of the substance scattering over great distances. Bodies hundreds of kilometers in diameter formed a layer tens of kilometers in thickness after the fall. Differences in its composition from the mean by just several percentile points could result in a marked heterogeneity.

More definite conclusions can be drawn about the thermic heterogeneities which are formed as a result of a large amount of energy being liberated when large bodies fall. As a result of the destruction of substances in the vicinity

of the crater by the shock wave, and as a consequence of the ejected substance falling back again, there is formed under the crater a layer of disintegrated rock (breccia). The results obtained from drilling in the craters of Hollyford and Brent agree with the theoretical considerations by Rottenberg to the effect that in the granito-gneisses the depth of the breccia in the central part of the crater should be about one-third the diameter of the crater [19]. In the zone of disintegration the pressure on the front of the shock wave is greater than the density of the rocks and the oscillations are inelastically propagated. Beyond the limits of this zone the disturbance is propagated in the form of elastic oscillations (seismic waves) whose dampening is considerably slower. As a first approximation, the volume of destroyed rocks is proportional to the total energy of impact by the body [19,20].

The formation of a vast zone of breccia resulting from large fallen bodies gives rise to two kinds of heterogeneities in the earth's mantle:

1) The density of the substance in this region is lower than in that of the surrounding substance that had not been subjected to destruction. According to data obtained by drilling, which were supported by independent evaluations of measured values of gravitational anomalies, the difference in densities is an average 0.2 g/cm^3 [19]. The volume of breccia exceeds by several times the volume of the crater and, therefore, it is considerably greater than the volume of the fallen body. Therefore, heterogeneities in density which arise when bodies fall can be considerably greater than those which were discussed in the preceding section;

2) On the basis of general considerations one might expect in the breccia zone a transition to heat of a considerable quantity of energy of the shock wave. Thus far, there is no strict theory existing which would permit one precisely to determine what portion of the energy of a fallen body goes

into the destruction of matter, what portion goes into the production of heat, and what portion for the ejection of the substance or matters. Opinions among the different authors differ greatly on this score. Using a simplified striking mechanism, Opik [21] made a study of the degree of heating of a substance in the impact zone. Given a rate of fall of 10 km/sec, matter on a wave front surface which embraces 30-fold the mass of the fallen body, is heated to 580°, on a surface which embraces 50-fold the mass it is heated to 208°, and on a surface which embraces 75-fold the mass of the fallen body matter is heated to 93° C. Disregarding the proximity and the overestimate of this calculation it is apparent that a considerable mass of the substance in the impact zone (much greater than the mass of the fallen body) is heated to hundreds of degrees. The thickness of the heated layer is greater than the diameter of the fallen body and the horizontal dimension is of an order greater than the diameter.

It follows that the growth of the earth due to the dropping upon it of small bodies and particles is accompanied by the liberation of heat in the thin surface layer. This heat was radiated into space, for the main part, and it resulted in the comparatively uniform heating of the entire earth. When larger bodies fell to the earth the heat was given off at great depths and a considerable portion of it remained in the earth's subsurface creating an excessively heated region in its mantle.

We can compute the dimensions of bodies capable of producing thermic heterogeneities. We can get some idea about the speed of cooling of the flat layer near the surface of the earth from a solution of the equation for thermal conductivity without sources for a semi-infinite straight line with constant temperature on the boundary [22]. At initial and boundary conditions

$$T(x,0)=\begin{cases} T_1 & 0<x<h \\ 0 & x>h, \end{cases} \quad T(0,t)=0 \tag{4}$$

the solution is
$$T(x,\ t)=\frac{T_1}{2}[2\Phi(y)-\Phi(y-y')-\Phi(y+y')],$$
$$\Phi(y)=\frac{2}{\sqrt{\pi}}\int\limits_0^y e^{-y^2}\,dy, \qquad (5)$$

in which $y = x / 2\sqrt{kt}$; $y' = h / 2\sqrt{kt}$; k is the coefficient of temperature conductivity. The temperature in the middle of the layer $x = h / 2$ is equal to

$$T_c=T\left(\frac{h}{2},t\right)=\frac{T_1}{2}\left[3\Phi\left(\frac{y'}{2}\right)-\Phi\left(3\frac{y'}{2}\right)\right]. \qquad (6)$$

When $y' = 3$, T_c is only 5% less than the initial value of T_1. The flow of heat from the exterior surface of the layer to the surrounding space is equal to

$$H=kc\rho\left(\frac{\partial T(x,t)}{\partial x}\right)_{x=0}=\frac{T_1 kc\rho}{\sqrt{\pi kt}}(1-e^{-y'^2}). \qquad (7)$$

The energy radiated by 1 cm^2 of surface from the instant it begins to cool to moment t:

$$E=\int\limits_0^t H\,dt=\frac{E_0}{\sqrt{\pi}}\left[\frac{1}{y'}(1-e^{-y'^2})+\sqrt{\pi}(1-\Phi(y'))\right], \qquad (8)$$

in which $E_0 = c\rho T_1 h$ is the initial energy of the layer per 1 cm^2; $E = \frac{1}{2} E_0$ when $y' = 1.04$. This means that during the time corresponding to $Y' = 1.04$ the layer dissipates to external space half of its thermal energy. During the process of growth by the earth the heated layers were covered over from above by matter and the radiation of their heat from the surface of the earth was less than that found in the above. If the thickness h of the heated layer is such that during the time t with $y' = 1.04$ there is poured upon it a new layer of matter with a thickness of the order of h then less than half of the heat of the heated layer is radiated and the remainder stays inside the earth. This is evident from the fact that the cooling time of a layer

increases as the square of its thickness. We therefore say that h = tdR/dt in which the rate of accretion of the radius of the earth dR / dt is determined by expression [11]

$$\frac{dR}{dt} = \frac{(1 + 2\theta)\sigma}{\delta P}, \tag{9}$$

in which δ is the density of the upper layers of the earth; P is the period of its revolution about the sun; σ is the surface density of the unscooped substance in the earth's zone. Then

$$h = 2y'\sqrt{kt} = 2{,}08\sqrt{k\frac{h}{dR/dt}} = 2{,}08\sqrt{\frac{kh\delta P}{(1 + 2\theta)\sigma}},$$

i.e.,

$$h = 4{,}3\frac{k\delta P}{(1 + 20)\sigma} = 4{,}3\frac{k\delta P}{(1 + 20)\sigma_0(1 - M/Q)}, \tag{10}$$

in which σ_o is the total surface density (including the substance of the earth); M is the mass of the earth in the epoch under consideration; Q is the present mass of the earth. Assuming k = 0.005, δ = 3 g/cm^3, P = 3 $\cdot$ 10^{-7} sec, σ_o = 10 g/cm^2, we find

$$h = \frac{2\cdot 10^5}{(1 + 2\theta)(1 - M/Q)}. \tag{11}$$

A depth of the order of 500 km corresponds to M/Q $\approx$ 0.7. Thence, with θ = 3 we get h $\approx$ 1 km. The thickness of a heated layer is of the order of the diameter of the fallen body. Consequently, in the case of falling bodies with diameters of over a kilometer, a considerable portion of the impact energy given off in the region under the crater could not be carried off through the usual process of thermal conductivity to the outside. A considerably more effective method of carrying off the heat to the surface was the intensive shifting of matter by the impact of falling bodies. When bodies drop at velocities of 10-12 km/sec the mass of material ejected from the crater exceeds the mass of the fallen body by two or three orders. Hence, each element of

volume of earth substance is ejected outward and become mixed hundreds of times before it is finally buried under the layers pouring in from above. By way of an analog of the coefficient of thermal conductivity in such a case we can take the value $k(z) \sim z^2/\tau$, where τ is the interval of time between two successive mixings (ejections) of matter at depth z. k(z) depends on the function of distribution by dimensions of falling bodies and grows from z to a depth of several hundred kilometers. In this case it exceeds, on an average, by two or three orders the usual coefficient of temperature conductivity k. Thus, the question about the initial temperature of the earth is considerably more complex than in the case of several bodies falling when the energy of impact is released practically on the surface and is radiated off for the most part. A large part of the energy of fall of large bodies remained inside the earth and was capable of heating the area of the upper mantle in excess of $1,000^{\circ}$.

Marked temperature heterogeneities of the mantle could be created only by the largest bodies. Given in the table is the temperature T_c of the central part of a layer of thickness h 10^8 and 10^9 years after the cooling process commenced as computed by formula (6) and expressed in units of initial temperature T_1.

In a layer of thickness 200 - 250 km the temperature of the central portion is lowered only by 5 - 10% in 10^8 years (time of earth's growth). In 10^9 years there still remains in the center of the layer surplus energy that is 20-30% of the original temperature, i.e., of the order of 100° C if the layer had been heated to 500° C. Consequently, bodies with radii over 100 km should produce marked thermic heterogeneities in the forming earth during their fall. Larger heterogeneities were preserved for one to two billion years, i.e., during the time when, because of the intensive heating of the

earth by radioactive heat, the viscosity of its matter changed considerably and gravitational differentiation began. In the regions of the upper mantle with a temperature surplus of 100-150° C caused by the fall of large bodies the melting of core matter should have commenced 100 million years earlier than in other zones.

t, yrs.	h, км 30	50	100	150	200	250
		T_c/T_1				
10^8	0,03	0,11	0,44	0,72	0,89	0,96
10^9	0,001	0,004	0,032	0,09	0,19	0,29

As previously mentioned by E. L. Ruskol [23] the dissipation of energy of lunar tides in the hard body of the earth could have occurred, mainly, in the more highly heated portions of the upper mantle with lowered elasticity of substance, and imparted to them additional heating. Because of this source of energy thermic heterogeneities were preserved for a prolonged period of time, and, possibly, even become intensified. Relaxation of thermoelastic tensions in zones with marked temperature gradients [24] (i.e., on the periphery of the heterogeneities under consideration), especially in plastic deformations [25], resulted in still another supplemental source of heating which acted in this same direction. Hence, the areas of impact of the larger falling bodies during the time of formation of the earth became converted into relatively stable areas of increased temperature in which all the processes associated with the melting of the core and tectonic activity began earlier and flowed along more intensively. The most marked heterogeneities must have resulted from the fall of bodies with diameters of several hundred kilometers and their horizontal dimensions exceeded a thousand kilometers.

The mechanism described opens up possibilities for explaining the reasons for the differences between continents and oceans. Despite the existence of many factors exerting an influence on the complex process of evolution

of the earth, an important role is apparently attributable to the initial thermic heterogeneities, and they should be taken into account in a study of this process.

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